

entire island. In class B the center was not more than 50 miles distant, while in class C the center was more than 50 miles distant. Hence the importance of anticipating the exact distance of the center from any portion of the island on the approach of a hurricane.

With this statement of the basis of hurricane classification we may examine the list of storms recorded in the vicinity of Porto Rico since the historic storm of August 8, 1899.

TABLE I.—List of hurricanes in the vicinity of Porto Rico (1899–1929)

	Class		Class
1899: Aug. 8 (San Ciriaco)-----	A	1916: Aug. 22-----	B
Sept. 9-----	C	Aug. 29-----	C
1900, Sept. 1-----	C	Oct. 10-----	B
1901, July 7-----	C	1917, Sept. 21-----	C
1906, Sept. 3-----	C	1919, Sept. 3-----	C
1908, Sept. 10-----	C	1921, Sept. 10-----	C
Sept. 27-----	C	1922, Sept. 17-----	C
1909, Aug. 22-----	B	1924, Aug. 29-----	C
1910, Sept. 6-----	B	1926, July 23-----	B
1915, Aug. 11-----	B	1928, Sept. 13 (San Felipe)-----	A

On examination of the official records we may place the storms of this period in the following groups:

Class	Number of storms	Percentage	Dates
A	2	10	Aug. 8, 1899 (San Ciriaco); Sept. 13, 1928 (San Felipe).
B	6	30	July, 1926; August, 1909, 1915, 1916; September, 1910; October, 1916.
C	12	60	July, 1901; August, 1916, 1924; September, 1899, 1900, 1906, (2) 1908, 1917, 1919, 1922, 1921.

The total number of storms recorded in Porto Rico for the 31 years from 1899 to date is 20. As already shown in the list of storms prior to 1899 the hurricane months are July, August, September, and October. Class A shows only two hurricanes in 31 years with an interval of 30 years; class B shows 6, with an average interval of 5 years, and class C shows 12, with an average interval of 2½ years. The distribution of the storms through the period is not at all even, however, as there are 2 periods of 4 consecutive years and 6 periods of 1 year without a storm of any class. There was but 1 storm in the month of October and only 2 in the month of July, confirming the common impression that the months of August and September constitute the real hurricane season in the vicinity of Porto Rico. Six storms are credited to August and 11 to September, but 9 of the 11 September storms were of the mild type, or class C.

As storms of class A were of such infrequent occurrence from 1899 to 1929 an effort was made to extend the period

for this class backward to the beginning of the nineteenth century. This may safely be done as storms of such violence would certainly be noted in any local chronicle of hurricanes. In looking over Alexander's list of hurricanes from 1800 to 1899 we find only two additional storms which seem to merit a place with San Ciriaco and San Felipe II, namely, Santa Ana (July 26, 1825) and San Narciso (October 29, 1867). Incidentally, San Narciso is the only storm recorded after the middle of October in a period of over 400 years. Los Angeles (August 2, 1837), Santa Elena (August 18, 1851), and San Felipe I (September 13, 1876), which are frequently quoted as historic storms, seem rather to have been of class B, so far as extent of damage in Porto Rico is concerned. The addition of these two storms of the nineteenth century will give us four storms of class A in a period of 130 years, with an average interval of 31 years.

As storms of class C are on the whole beneficial, owing to the value of the rains which they bring and the comparatively small property losses, we may disregard this class as a source of personal danger, eliminating the element of fear from 60 per cent of the total number of Porto Rican hurricanes.

Storms of class B are likewise attended by beneficial rains; but such benefits may or may not be overshadowed by heavy local property losses.

Storms of class A are a calamity and are responsible for the universal dread which seems to be inseparably connected with the word hurricane throughout the world. Hurricanes of the severest type, if their centers are more than 50 miles distant, are more likely to be beneficial than harmful, as winds exceeding 75 miles an hour seldom extend beyond this distance from the center.

Reviewing the statistics in the above tables and including class A hurricanes of the nineteenth century, we have the following hurricane frequencies for Porto Rico and vicinity:

Class	Number of storms	Period of years
A-----	4	130
B-----	6	31
C-----	12	31

While we may not be justified in concluding that these frequencies and proportions will hold good in the future we may say that the probabilities are in favor of the occurrence of 1 storm of class A, 6 storms of class B, and 12 storms of class C in the next generation. Even this broad statement may have some practical value in estimating probable losses to property and crops and in determining insurance rates.

THUNDER AND LIGHTNING IN THE SOUTH PACIFIC OCEAN

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In the South Seas and Southern Pacific Ocean violent thunderstorms are not of frequent occurrence. In my nine years' residence in Samoa I have only experienced 2 electrical storms which compared in intensity with 5 or 6 per annum in southern Ontario and New England. Lightning, however, often occurs on the open ocean, but is probably most frequent in the vicinity of the island groups which dot the western half of the South Pacific. The research yacht *Carnegie* observed thunder or lightning on 27 of the 139 days she has spent during her fourth, fifth, and sixth cruises (1) within the Tropics of the South Pacific Ocean.

Continuous records of thunderstorms are available from Apia, Samoa; Suva, Fiji; Nauru; and Rarotonga. Other records with less sharp distinctions drawn between thunder and lightning have been obtained from Papeete, Tahiti; Nassau; and Niue Islands. Discrepancies in the records show that observers used widely differing ideas of a thunderstorm, the occurrence of lightning being frequently not recorded.

In Table 1 is given the number of days thunder was recorded at the most reliable stations.

TABLE 1.—*Monthly variation of days with thunder at stations in the South Pacific Ocean*
 [The mean has been derived only from those stations in the trade-wind area marked with asterisks]

	Lat.	Long.	Years	January	February	March	April	May	June	July	August	September	October	November	December	Total
Apia.....	13.8 S	171.8 W	1923-1929.....	2.8	2.4	2.2	3.4	1.6	1.6	0.8	1.0	1.9	4.4	6.2	4.8	32.6
Apia (2).....	13.8 S	171.8 W	1891-1929.....	4.1	3.3	4.4	3.7	2.5	1.7	.7	.5	1.2	2.8	4.7	5.2	34.3
Suva (3).....	18.2 S	178.5 E	1923-1929*.....	2.4	2.9	3.3	3.3	1.0	.9	.7	.4	.3	1.0	1.7	2.4	20.3
Chatham Islands (4).....	43.9 S	170.7 W	26 years.....	1.2	.9	.4	.6	.9	.6	.8	.5	.5	.5	.5	1.0	8.2
Rarotonga (5).....	21.2 S	159.2 W	10 years.....	2.2	1.9	1.9	.9	1.1	.7	.7	.5	.5	.9	.8	1.0	13.1
Batavia (6).....	6.2 S	106.8 E	10 years.....	13.3	12.5	14.4	14.0	11.0	8.0	5.9	5.0	7.4	12.4	16.0	13.2	133.1
Nauru (5).....	.4 S	166.9 W	6 years*.....	.7	1.7	.3	.2	.5	1.0	1.2	.2	.5	.2	.2	.2	6.2
Mean.....				2.3	2.4	2.5	2.0	1.3	1.1	.8	.4	.6	1.2	1.8	2.2	18.4

TABLE 2.—*Monthly variation of days with either thunder or lightning*

	Lat.	Long.	Years	January	February	March	April	May	June	July	August	September	October	November	December	Total
Apia.....	13.8 S	171.8 W	1925-1929.....	5.4	4.6	5.2	7.8	4.6	5.4	1.4	3.4	4.0	8.6	9.6	9.2	69.2
Do.....	13.8 S	171.8 W	1891-1907.....	5.6	4.2	5.7	5.2	3.1	1.8	1.0	.7	1.4	5.1	4.9	5.6	44.3
Suva.....	18.2 S	178.5 E	1927-1929.....	2.7	2.7	4.7	3.0	.3	2.7	-----	1.0	.7	2.0	3.3	7.0	30.1
Papeete.....	17.5 S	149.5 W	1925-1929.....	2.0	2.4	3.5	1.2	.4	.2	.4	.0	.0	1.2	.4	2.0	13.7
Niue.....	19.0 S	169.9 W	1926-1929.....	.8	2.2	3.8	1.0	.3	.0	.7	.7	1.7	1.3	.0	4.0	16.5
Nassau.....	11.6 S	165.4 W	1928-29.....	.5	1.0	2.0	2.7	1.3	.5	1.5	-----	1.0	2.0	2.5	-----	15.0
Rarotonga.....	21.2 S	159.2 W	1899-1909.....	3.1	2.9	3.3	1.5	2.1	1.0	1.3	.8	.9	1.4	1.2	1.0	20.5
Nauru.....	0.4 S	166.9 W	1893-1901.....	1.0	2.0	1.0	.6	1.6	2.4	1.0	1.5	1.0	1.1	1.3	2.1	16.6
Mean.....				2.2	2.5	3.4	2.2	1.3	1.2	.8	.7	.9	2.0	1.9	3.1	28.2

Careful distinction must be made to note exactly the phenomena the observer has recorded. Thus, at Suva during the three years 1927-1929 atmospheric electric phenomena were recorded on 90 days, out of which lightning only was observed 82 days and thunder only on 62 days. When days with either lightning or thunder are included (Table 2) the figures are much altered from those given in Table 1.

Owing to the frequency and regularity of heat or summer lightning, observers almost invariably fail to record it. Often only one or two clouds are for an instant illumined by a glow. The lightning flashes pass from cloud to cloud, but rarely go down to the surface of the ocean. Some observers in Samoa have (7) believed the lightning to occur most frequent during the daytime over the mountain peaks and in the evening out to sea. During March and April, 1930, lightning has been persistently, both afternoon and evening, more common out to sea. Thunder rarely accompanies these displays of lightning. Over 100 flashes have been seen in three hours without a single peal of thunder having been heard.

In the south seas the yearly variation of days with thunder has a single flat maximum from December to March, with a pronounced minimum in August and September. The rainy season, in which at Apia 74 per cent of the rainfall occurs, covers the period November to April. During this period the southeast trade winds blow intermittently and are often interrupted by northeast and northwest winds and by calms. At Apia lightning does not show the pronounced minimum in the dry season from May to October that occurs with thunder. There are indications of two maxima in April and October, months that mark the setting in and cessation of the trade winds.

DIURNAL VARIATION OF THUNDER

An unusually careful record of the exact hour of occurrence of thunder and lightning was begun by Dr. B. Funk at Apia in January, 1891, and continued, except for absences amounting to one and one-half years, to December, 1899. During this period the time of thunder was recorded on 235 occasions to the nearest quarter of an hour and on 41 entries to a fairly definite time as "during the night," "toward morning," or "very early." After these 41 entries have been allocated the occurrence of thunder for each period of two hours is given in Table 3. The great difficulty has always been to obtain complete thunder records during the night hours from,

say, 11 p. m. to 6 a. m. However, Doctor Funk had unusual opportunities for securing data, and his observations show meticulous care in noting whether thunder or lightning occurred.

TABLE 3.—*Average hourly frequency of thunder, negative electrical potential of the atmosphere, and rainfall at Apia, Samoa*

	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24
Average number of hourly periods thunder was recorded per annum.....	1.3	1.4	1.1	1.1	0.9	2.1	2.1	2.7	1.8	2.0	2.4	1.4
Average number of hourly periods negative electrical potential of atmosphere was recorded per annum.....	3.3	3.3	3.2	2.8	2.8	3.0	4.2	4.0	3.6	3.2	3.4	3.6
Mean rainfall per hour in tenths of millimeters.....	3.2	3.4	3.1	2.7	2.4	2.4	2.7	3.9	3.9	3.7	3.4	3.0

G. R. Wait (9) has shown that there is probably a close relationship between the occurrence of thunderstorms and of negative electrical potential of the atmosphere. Since records of electrical potential are obtained by a self-registering electrometer the results are entirely free from the human element. In three years' records from 1925 to 1927 the occurrence of negative electrical potential for the hours from midnight to 4 a. m. was slightly below the mean for the day. In view of the close association of negative electricity with thunderstorms, the atmospheric electric data confirms Doctor Funk's observations that thunder occurs less frequently from midnight to 9 a. m. than during the rest of the day. The minimum for the 24 hours occurs from 9 a. m. to 10 a. m. The frequency of thunder increases sharply after 10 a. m. and reaches a maximum during the afternoon from 1 p. m. to 4 p. m. A pronounced but short period of comparative rarity of thunder extends from 4 p. m. to 7 p. m., thunder during this period being one-third less frequent than during the afternoon and evening hours. From 7 p. m. to 11 p. m. thunder was recorded almost but not quite as often as in the early afternoon. The afternoon maxima occurs at the same hours as the heaviest and most frequent rainfalls. The evening maximum would appear to be caused by convection currents in the lower stratum of air. Lightning occurs three times as frequently from 7 p. m. to 10 p. m. as at any other period of the day.

According to a frequently quoted article by W. Meinardus (10) the period of maximum thunderstorms over the ocean occurs from midnight to 4 a. m. Conditions at Samoa are probably typical of those prevailing on the open ocean in the trade-wind belt of the South Pacific, and for this area the results are at variance with those stated by Meinardus.

Apart from the difficulty of securing ships' logs, it is not easy to determine from them the definite occurrence of thunder and lightning on the open ocean. The only useful records I have obtained were 221 days' observations (Table 3) taken by the nonmagnetic yacht *Carnegie* while cruising mostly far from land between the Equator and the Tropic of Capricorn (1). In the western half of the tropical Pacific, thunder or lightning was recorded on 33.8 per cent of the days, while in the eastern half on 3.1 per cent of the days. This high frequency indicated clearly that electrical storms are as common at sea as in the vicinity of small tropical islands. The excess over the total recorded by the island observers arises largely from the continuous watch kept on the *Carnegie* during the night hours.

TABLE 4.—Frequency of thunder and lightning on open ocean within South Tropic Zone, from log of yacht "Carnegie," 1915-1921

	Days of observations	Days of lightning only	Days of thunder with or without lightning	Percentage of days with electrical storms
Western Pacific, west of longitude 140° W----	74	16	9	33.8
Eastern Pacific, east of longitude 140° W----	15	1	1	3.1
Total-----	139	17	10	19.4

Geographical distribution.—Although the data are scanty, it is apparent that thunderstorms are much more frequent

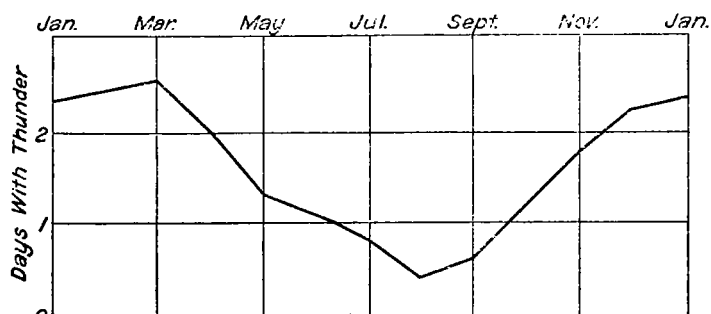


FIGURE 1.—Average number of days with thunder per month at four stations in the southwest Pacific

in the western Pacific than in the central or the eastern Pacific. According to reports from Papeete, Tahiti, lightning has been observed only about 16.6 days per annum, compared with 56.8 per annum at Apia. The *Carnegie* has recorded thunder and lightning ten times as frequently in the Southern Pacific west of the one hundred and fortieth west meridian as east of this meridian.

In the eastern Pacific the trade winds blow more strongly than in the western Pacific. Cyclones are very rare east of the one hundred and fortieth west meridian. The southeast wind circulation probably reaching greater heights than in the western Pacific and the uniformity and considerable velocity of the air stratum up to 7 or 8 km. are probably effective factors in reducing the number of thunderstorms east of the one hundred and fortieth meridian.

Local causes of thunderstorms.—Thunderstorms occur most frequently when strong vertical air currents are set up by a high temperature lapse rate in the rain-cloud stratum of the atmosphere. The conditions when either the vertical currents are sufficiently strong or the temperature lapse rate sufficiently high are as follows:

(1) *Tropical cyclones.*—Especially in low latitudes before the passage of a few tropical cyclones violent

thunderstorms occur. In a cyclone on December 25, 1926, violent thunderstorms accompanied the passage of the center over the Union group, latitude 8° S., but when passing over eastern Samoa, latitude 16° S., no thunder occurred.

(2) *The "clash of the northeast and southeast trades"* (11).—Instead of an extensive doldrum area, as in the Atlantic, the northeast and southeast trades in the Pacific run rather abruptly into one another. Along the line of meeting there must be turbulence, with strong upward vertical currents between the conflicting air masses. The line of meeting varies with the season from probably 10° N. to 10° S. latitude.

(3) *The mixing of the cold southwest countertrades with the surface southeast trades which they overrun.*—The height which the trades reach varies from nothing up to 3 or 4 km. Pilot-balloon observations have in general shown a very thin stratum between the southeast trades and the countertrades. Now when the air layers over the ocean are warmed by insolation, the evenness of the dividing surface is interfered with and air masses with considerable temperature differences are brought in contact with one another. After the sun goes down the most rapid temperature fall for 60 minutes occurs at the surface between either 5:30 p. m. and 7 p. m., depending on latitude. At levels 1 to 4 km. the rate of fall would probably be delayed for some hours.

(4) An unusual cause for lightning in Samoa in former years was the active volcano Matavanu, in Savai'i.

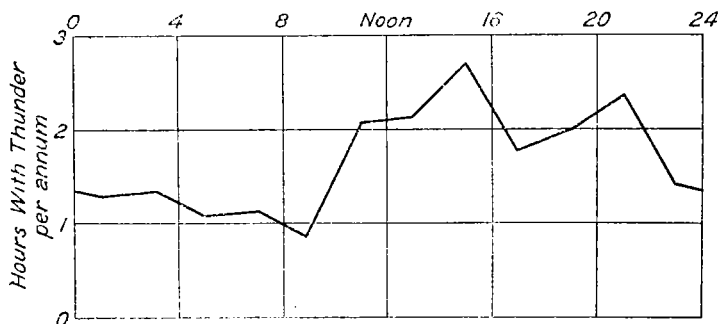


FIGURE 2.—Hourly frequency of thunder at Apia, Samoa. Maximum at 15h is due to rain and at 21h to convection currents from high lapse rates after sunset

The strong convection currents rising from the crater and from the fields of hot lava produced cumulus clouds, which were frequently illumined by flashes of lightning.

Losses from lightning.—In nine years in the Samoa and Fiji groups, with a total population of 200,000, two people have been reported struck by lightning and killed. Occasionally the tops of the tall coconut palm trees are shattered. In February, 1922, a schooner in Apia Harbor was struck by lightning, her foremast was splintered, and the direction of her compass needle altered by 20°. Property damage from lightning is almost negligible in the islands of the South Pacific.

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